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FISSION PRODUCT TRAPS FOR USE IN HIGH-TEMPERATURE
GAS-COOLED GRAPHITE REACTORS

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FISSION PRODUCT TRAPS FOR USE IN HIGH-TEMPERATURE, GAS-COOLED GRAPHITE REACTORS

Introduction

In the design of a high-temperature, helium-cooled reactor the problem of the diffusion of fission products from the graphite-clad fuel elements into the coolant (with the subsequent deposition of radioactivity throughout the primary circuit) must be solved.¹ It has been suggested that fission products which would tend to diffuse out of the fuel elements (excepting krypton and xenon) might be trapped by a chemically reactive agent operating at an elevated temperature before they get into the main coolant stream.² This might be possible with an arrangement where the trap is placed in a cool portion of the fuel element (or an extension thereof) and a pressure drop and suitable ducts are provided so that a portion of the coolant gas will flow through the pores of the graphite cladding into the fuel region and then along a duct to a fission product trap and finally return to the main stream of the coolant.

It is the purpose of this report to propose a fission product trap system which tentatively appears feasible on the basis of the best thermodynamic and other data that is available. However, an answer to the question of feasibility (quite aside from questions of a practical engineering or economic nature) can be provided only by laboratory experiments designed to test the actual behavior of trap components and the system as a whole. Thus this report can only provide an indication of a general approach and suggest specific experiments which will have to be carried out to establish the feasibility of fission product traps.

Conditions in the Reactor

It is understood the uranium carbide-thorium carbide-graphite fuel slug inner temperatures will be of the order of 1500°K and the graphite cladding

material temperature may be as high as 1200°K. Also it is understood there will be approximately 520 fuel elements with a total coolant flow of 61.4 pounds of helium per second at a pressure of about 15 atmospheres. The following assumptions have been made which are pertinent to fission trap considerations:

1. Trap temperature: 1000°K, 700°K, or 625°K
2. Volumetric flow rate of helium passing into one fuel element: 0.1 cm³/sec
3. Forty-five grams of U²³⁵ (or its equivalent) fission per year per fuel element $\approx$ 192 millimoles of fission per year

Assuming that at the steady state the fraction, f , of a given fission product is carried by the helium (0.1 cm³/sec) to the trap, the partial pressure of the fission product (as a monatomic gas) is given by:

$$P = 2.5 \times 10^{-8} TYf \text{ (atm)} \quad (1)$$

where

T = absolute temperature (°K)

Y = fission yield (%)

Ideally the fraction $1 - f$ of the fission product is retained in the fuel slugs which may be encased in relatively impervious graphite cans.

In the case of poor retention, where $f \approx 1$, relatively high partial pressures of fission products can be expected. Thus for I¹³¹ at 700°K:

$$P_{I^{131}} = 5.1 \times 10^{-5} = 10^{-4.29} \text{ atm.}$$

Fission Products of Interest

Let us first list the fission products which appear to be the most serious from the point of view of their possible diffusion out of fuel elements and deposition in the primary circuit. These are by virtue of their volatility, fission yield and half-life, the following:

<u>Element</u>	<u>Isotope</u>	<u>Fission Yield</u> <u>(U²³⁵)⁷</u>	<u>Half-Life</u> ⁷	<u>Radiation</u>	<u>Millimoles</u> <u>yr-fuel element</u>
Strontium	Sr ⁸⁹	4.8%	51d	No γ	9.2
	Sr ⁹⁰	5.8	28y	"	11.1
Antimony	Sb ¹²⁵	0.024	2.4y	β, γ	0.046
	Sb ¹²⁷	0.13	93h	"	2.5
Tellurium	Te ¹²⁹	4.3	33d	"	8.3
Iodine	I ¹³¹	2.9	8.0d	"	5.6
Cesium	Cs ¹³⁷	6.0	30y	"	11.5
Barium	Ba ¹⁴⁰	6.4	12.8d	"	12.3

Fission products of the following elements will probably show little void-space diffusion in fuel elements or a tendency to vaporize therefrom because of their low volatilities.³

<u>Element</u>	<u>Vapor Pressure (atm)⁴</u>	
	<u>1500°K</u>	<u>1000°K</u>
Zr	10 ^{-14.0}	10 ^{-24.5}
Nb	10 ^{-18.0}	10 ^{-30.9}
Mo	10 ^{-15.2}	10 ^{-26.5}
Tc	10 ^{-15.0}	10 ^{-26.3}
Ru	10 ^{-12.8}	10 ^{-23.3}
Rh	10 ^{-11.5}	10 ^{-21.1}
Pd*	10 ^{-7.2}	10 ^{-14.0}

* Palladium should be classed as slightly volatile at 1500°K.¹⁰⁹ Its most important fission product isotope is 13.6 hour Pd¹⁰⁹ (no γ) with a U²³⁵ fission yield of 0.03%.

Yttrium and the rare earths form stable carbides and are considered by Brewer, et al⁵ to be non-volatile (vapor pressure $< 10^{-7}$ atm) at 1500°K. The vapor pressure of Y and R.E. metals and the estimated equilibrium pressure of the metals over their carbides are as follows:

Element	Vapor Pressure of element (atm) ⁴		Estimated pressure ⁺ of element over carbide at 1500°K
	1500°K	1000°K	
Y	$10^{-8.0}$	$10^{-15.4}$	(10^{-12})
La	$10^{-8.2}$	$10^{-15.3}$	(10^{-12})
Ce	$(10^{-5.8})^*$	$(10^{-11.3})^*$	$10^{-9.5}$
Pr	$(10^{-6.3})$	$(10^{-12.2})$	(10^{-10})
Nd	$10^{-5.7}$	$10^{-11.0}$	(10^{-9})
Pm	$(10^{-5.1})$	$(10^{-10.4})$	(10^{-9})
Sm	$10^{-1.34}$	$10^{-4.9}$	(10^{-5})
Eu	$10^{-0.64}$	$10^{-3.5}$	(10^{-4})
Gd	$10^{-5.5}$	$10^{-11.5}$	(10^{-9})
Tb	$(10^{-4.8})$	$(10^{-10.2})$	(10^{-8})

* Values of the vapor pressures in parentheses were estimated from melting point, heat of fusion, boiling point and heat of vaporization data given by Stull and Sinke.³

⁺ The estimate for Ce is based on data given by Krikorian.⁶ Values in parentheses are based on the guess that the standard free energy of formation of the Y and R.E. carbides is about -25 kcal/gm atomic wt of the metal at 1500°K.

It would appear from this data that the fission products of samarium and europium will tend to show significant void-space diffusion and vaporization from graphite fuel elements even though they may form relatively stable carbides. The fission product isotopes of Sm and Eu of interest are:

<u>Isotope</u>	<u>Fission Yield</u>	<u>Half-Life</u> ⁷	<u>Radiation</u>
Sm ¹⁵¹	0.45%	~100y	β, γ low energy
Sm ¹⁵³	0.15	47h	β, γ weak
Eu ¹⁵⁵	0.033	1.7y	"
Eu ¹⁵⁶	0.014	15.4d	β, γ
Eu ¹⁵⁷	0.008	15.4h	"

Of these isotopes, Eu¹⁵⁵ and Eu¹⁵⁶ have sufficiently high fission yields and half-life and radiation characteristics such that they could make an appreciable contribution to the contamination of the primary circuit. On the other hand, it appears that the fission products of cerium (Ce¹⁴¹, Ce¹⁴³, Ce¹⁴⁴) which are potentially serious contaminants would tend to be stabilized as carbides and have a quite low partial pressure as the monatomic gas in equilibrium with the carbide at 1500°K.

The fission product elements germanium, gallium, silver and tin might be classed as being of intermediate volatility. The vapor pressure of these elements (as the monatomic gas over the metal) is less than 10^{-8} atmospheres at 1000°K. Accordingly, these elements will tend (under reducing conditions) to come out on a trap at temperatures of around 1000°K or less. The element indium is also relatively non-volatile and will be readily condensed on a trap at 700°K (vapor pressure of the element is 10^{-12} atm). The vapor pressures of these elements at 1500°, 1000°, and 700°K are as follows:

<u>Element</u>	<u>Vapor Pressure (atm)</u> ⁴		
	<u>1500°K</u>	<u>1000°K</u>	<u>700°K</u>
Ga	$10^{-3.65}$	$10^{-8.2}$	$10^{-14.2}$
Ge	$10^{-6.10}$	$10^{-12.4}$	$10^{-20.9}$
Ag	$10^{-3.52}$	$10^{-8.3}$	$10^{-14.6}$
In	$10^{-2.81}$	$10^{-6.8}$	$10^{-12.0}$
Sn	$10^{-5.01}$	$10^{-10.1}$	$10^{-16.7}$

The balance of the fission product elements are relatively volatile at 700°K (strontium and barium being the least volatile with vapor pressures of $10^{-6.5}$ and $10^{-7.6}$ atm respectively).⁴ Of these, the following elements are relatively unimportant as contaminants because of the low fission yields and/or the half-lives of their fission produced isotopes:

<u>Element</u>	<u>Isotope</u>	<u>Fission Yield (U^{235})⁷</u>	<u>Half-Life⁷</u>
zinc	Zn ⁷²	$1.6 \times 10^{-5}\%$	49.h
arsenic	As ⁷⁷	0.008	27.h
	As ⁷⁸	0.021	91.m
selenium	Se ⁷⁹	0.056	$\leq 6 \times 10^4$ y
	Se ^{81m}	0.14 (chain yield)	57 m
	Se ⁸¹	"	18 m
bromine	Br ⁸²	3.5×10^{-5}	36.h
	Br ⁸³	0.54	2.3 h
	Br ⁸⁴	1.0	32.m
rubidium	Rb ⁸⁶	3.1×10^{-5}	19.d
	Rb ⁸⁷	2.5	5×10^{10} y
	Rb ⁸⁸	3.6	18.m
cadmium	Cd ^{115m}	8×10^{-4}	43 d
	Cd ¹¹⁵	0.011	53 h
	Cd ^{117m}	0.011 (chain yield)	2.9 h
	Cd ¹¹⁷	0.011	~50 m

Reagents for Fission Product Traps

In accordance with the above, it is evident that a fission product trap will have to be effective in holding both volatile non-metals (or near non-metals) such as iodine, tellurium and antimony and volatile metals such as cesium, barium and strontium. In order to provide for the most effective retention at elevated temperatures two types of reagents are required. Type I, a highly electropositive metal that will not melt or appreciably vaporize and which will form stable non-volatile compounds with non-metallic or near non-metallic fission products; and Type II, a reagent that will provide a

highly electronegative element which will form stable, non-volatile compounds with metallic fission products.

The electropositive metals which at the outset appear to be candidates for Type I reagents are: the group three elements yttrium and lanthanum for higher trap temperatures (1000°K) and the group two elements, calcium, strontium and barium for lower trap temperatures (700°K or 625°K). The melting points (T_m) and vapor pressure of these elements at 1000°K and 700°K indicate their suitability. These are as follows:

Element	T_m $^{\circ}\text{K}$	Vapor Pressure (atm)	
		1000°K	700°K
Y	1,773	$10^{-15.4}$	$10^{-24.9}$
La	1,193	$10^{-15.3}$	$10^{-24.6}$
Ca	1,123	$10^{-3.55}$	$10^{-7.37}$
Sr	1,043	$10^{-2.90}$	$10^{-6.45}$
Ba	983	$10^{-3.86}$	$10^{-7.64}$

It is to be noted that strontium is appreciably volatile at 700°K . However, the vapor pressure of $10^{-6.45}$ atm at 700°K corresponds to a maximum loss of only 1.7 mg strontium per year due to the sweeping action of helium flowing at the rate of $0.1 \text{ cm}^3/\text{sec}$. More important criteria for the optimum reagent are the stability and the volatility of the compounds they will form with the fission products.

Let us first consider the compounds with iodine for which there is much more thermodynamic data available than is the case with the compounds of tellurium and antimony. Data on the melting point and volatility of the iodides of the candidate Type I reagents follows:⁸

Compound	T_m °K	$T_{10^{-4} \text{ atm}}$ °K	$T_{1 \text{ atm}}$ °K	Vapor Pressure (atm) ⁺		
				1000°K	700°K	625°K
YI ₃	1273	(1010)*	(1580)*	10 ^{-3.9}	10 ^{-8.8}	10 ^{-10.8}
LaI ₃	1034	(1045)	(1675)	-	10 ^{-7.4}	10 ^{-9.2}
CaI ₂	1013	(900)	(1500)	-	10 ^{-6.3}	10 ^{-7.8}
SrI ₂	788	(1100)	(1850)	-	10 ^{-8.0}	10 ^{-9.7}
BaI ₂	984	(1150)	(2000)	10 ^{-4.9}	10 ^{-9.8}	10 ^{-11.8}

* Values in parentheses have been either estimated or extrapolated from experimental data by Brewer.⁸

⁺ Calculated from estimated data given by Brewer.⁸

It appears from the volatility data that barium is the best choice for the Type I reagent with yttrium running second. Furthermore, it is evident that a trap temperature of around 1000°K would be too high because the vapor pressure of the iodides are about 10⁻⁴ atmospheres at this temperature.* At such a vapor pressure we would have little hold-up of fission product iodine by the reagent since its partial pressure at the assumed flow rate of helium, as already noted, would have a maximum value of about 10^{-4.3} atm. On the other hand, at 700°K an equilibrium partial pressure of 10^{-9.8} for the iodide over the trap provides for the possibility of a substantial (> 10⁵ max) reduction in the concentration of fission product iodine in the helium which is swept through the reagent (Ba). With a trap temperature of 625°K the situation is still better. Thus, assuming $f = 10^{-4}$ in the case of I¹³¹ (i.e. all but 0.01% of this fission product is retained in the fuel slug) whereby it has a partial pressure of 10^{-8.3} atm in the flowing helium, an equilibrium pressure of 10^{-11.8} atm. I¹³¹ (as BaI₂) means an additional

* In the case of BaI₂, the vapor pressure is estimated to be 10^{-4.9} atm at 1000°K but the barium reagent would be fused at that temperature and could not be used in a finely divided solid form.

reduction in the escape of the fission product by a factor of $>10^3$ can be achieved to give an overall retention factor of $>10^7$. It is to be noted that the overall retention factor made possible by a chemical trap is independent of the retention in the fuel slug. Accordingly, if the trap has enough capacity, it will insure a large overall factor even though the fuel slug should fail to retain a given fission product.

The standard free energies of formation of the iodides at 700°K are as follows:

<u>Compound</u>	$\frac{\Delta F^\circ_{700^\circ}}{(\text{kcal/gm atom of iodine})}$
YI_3	-41
LaI_3	-50
CaI_2	-59
SrI_2	-63
BaI_2	-66

The large negative values of the free energy indicate the iodides to be quite stable relative to dissociation. Thus, the pressure of the monatomic iodine in equilibrium with BaI_2 and YI_3 at 700°K are estimated to be 10^{-24} and 10^{-16} atm, respectively.

In regards to the stability and volatility of the tellurides and antimonides of the group three and group two elements of interest, there is practically no data available. The following gives heat of formation data so that an idea can be obtained of the affinity of the candidate reagents for antimony or tellurium. In this tabulation the value of $-\Delta H^\circ_{298}$ which is a rough measure of the stability of the compounds listed (antimonides, tellurides and iodides) is given in units of kcal/gm atom of the non-metallic element.

Values of $-\Delta H_{298}^{\circ}$ for Compound*				
Metallic Element	Non-Metallic Element			
	<u>Sb</u>	<u>Te</u>	<u>I</u>	
	Y	(30)	(32)	55
	La	(55)	(52)	63
	Ca	87	65	73
	Sr	-	62	76
	Ba	87	64	80

* Values for antimonides and tellurides are taken from reference 10 except the values in parentheses which are rough estimates based on electronegativity considerations. Values for iodides are taken from reference 9.

It is seen that several reagents have affinities for antimony and tellurium comparable to that for iodine and, furthermore, that barium, in general, has a stronger affinity for the non-metals than does yttrium.

In regards to Type II reagents, volatility considerations lead one to the conclusions that: (1) cesium is the most difficult of the fission product metals to trap, and (2) the reagent might supply oxygen, fluorine or chlorine as the electronegative element. The melting points and vapor pressures of cesium oxide, fluoride and chloride are as follows:

<u>Compound</u>	<u>T_m</u>	<u>Vapor Pressure (atm)</u>		
		<u>1000°K</u>	<u>700°K</u>	<u>625°K</u>
Cs ₂ O	763	10 ^{-2.6*}	10 ^{-6.0}	10 ^{-7.6}
CsF	955	10 ^{-2.8†}	10 ^{-6.6}	10 ^{-8.1}
CsCl	918	10 ^{-2.8†}	10 ^{-6.9}	10 ^{-8.4}

* Calculated from estimates given by Glassner.¹¹

† Calculated from data given by Kubaschewski and Evans.¹⁰

It is evident from the data that the vapor pressures of these compounds are on the high side for the effective trapping of fission product cesium. One calculates (Eqn. 1) that at the maximum ($f = 1$) the partial pressure of Cs^{137} carried by the helium at $0.1 \text{ cm}^3/\text{sec}$ will be $10^{-3.98}$ atm. Thus at best, a trap at 700°K with a reagent which supplies oxygen, fluorine or chlorine would be able to reduce the concentration of Cs^{137} in the helium by a factor of less than 10^3 . In principle, the reduction of the concentration of Cs^{137} can be increased by arranging the trap so the radioactive cesium can exchange with stable cesium atoms in the form of a suitable compound (a hold-back agent) placed in the trap. Thus, a Type II reagent comprising a fluorinating agent such as FeF_3 could be used (which will convert Cs^{137} atoms to Cs^{137}F molecules) followed by a bed of ordinary cesium fluoride. In this bed the Cs^{137} atoms will tend to exchange with the ordinary Cs^{133} atoms and at equilibrium the partial pressure of Cs^{137}F over the cesium fluoride bed will equal the partial pressure of cesium fluoride at this temperature ($10^{-6.6}$ atm) times the mole fraction of Cs^{137}F in the cesium fluoride. For this to work in practice, the rate of exchange of Cs must be rapid relative to its rate of flow through the bed and this will depend on the particular compounds employed and the trap temperature. There is, however, a difficulty due to relatively high absorption cross section of stable cesium (Cs^{133}) and the fact that the trap may have to operate in a region of high neutron flux. It is estimated that at a flux of 5×10^{12} thermal $\text{n/cm}^2\text{sec}$ that 200 gm of ordinary cesium in a trap will yield 0.9 gm of $2.3 \text{ y } \text{Cs}^{134}$ per year and at the end of a year the Cs^{134} will have an activity 6.7 times that of the Cs^{137} (1.6 gm) produced in the fuel element.

In order to avoid the complication introduced by the production of Cs^{134} and the rather high absorption cross section of cesium ($\sigma_a = 29 \text{ barns}$)¹² the

use of isomorphous compounds of rubidium ($\sigma_a = 0.70$ b) as hold-back agents is suggested. Also it is to be noted that chlorine has a rather high thermal neutron absorption cross section ($\sigma_a = 31.6$ b) and for this reason probably should be eliminated from consideration as the electronegative element to be supplied by the Type II reagent.

In the case of the use of oxygen as the electronegative element the use of rubidium ^{Sesquioxide} Rb_2O_3 , appears to be a promising candidate for both the Type II reagent and the hold-back agent. It is isomorphous with Cs_2O_3 (having a cubic crystal structure corresponding to that of Th_3P_4 with the formula $\text{M}_4(\text{O}_2)_3$,¹³ and has the following properties which are listed with those of Cs_2O_3 .¹⁴

Compound	T_m °K	Partial Pressure of O_2 at 700°K atm	Decomposition Temperature °K
Rb_2O_3	762	$10^{-8.7}$	1043 (163mm O_2)
Cs_2O_3	775	$10^{-13.4}$	1125 (108mm O_2)

* Calc. from data and estimates given by Brewer.¹³

The oxides would have to be contained in something other than graphite--perhaps alundum--they attack carbon to form carbonates.

In the case of the use of fluorine as the electronegative element, two of a possible Type II reagents are FeF_3 and CeF_4 . Their properties are as follows:

Compound	T_m	Vapor Pressure (atm)		Partial Pressure of Cs(g) in equil. with compound (700°K)	Partial Pressure of F over Compound (700°K)
		1000°K	700°K		
FeF_3	1300	$10^{-3.9}$	$10^{-8.8}$	$10^{-21.}$	$10^{-19.}$
CeF_4	1250	$10^{-5.2}$	$10^{-10.3}$	10^{-32}	$10^{-7.5}$

Rubidium fluoride might be used as the hold-back agent in this case though cesium fluoride would be more effective. In any case, there is the question. Will the exchange be sufficiently rapid at a trap temperature of 700°K or 625°K?

It is to be noted that either oxygen or fluorine yielding Type II reagents will trap the highly electropositive group two (Sr and Ba) and group three (Y and rare earth) fission products quite effectively due to the high stability and low volatility of their oxides and fluorides.

The Transport of Materials and the Effect of Hydrogen

In regards to the transport of fission products, compounds of fission product and trap materials one calculates that at a flow rate of $0.1 \text{ cm}^3/\text{sec}$ one millimole per year is transported at the following equilibrium vapor pressures:

1500°K	1000°K	700°K	625°K
$10^{-4.41} \text{ atm}$	$10^{-4.59}$	$10^{-4.74}$	$10^{-4.79}$

Thus, very little reagent is lost in a year's time at vapor pressures of 10^{-5} atm or less.

There is the concern that a small amount of hydrogen in the coolant (10 ppm on a molar basis corresponds to a partial pressure of $10^{-3.82} \text{ atm}$) will cause trouble. In general, hydrogen will tend to react with Type II reagents leading to their depletion. Furthermore, in the case of a fluorinating or chlorinating agent (such as FeF_3 or CrCl_3) HF or HCl will be produced and thereby a corrosive agent will be introduced into the coolant. Fortunately, assuming reactor rates are adequate at the trap temperature, the Type I reagent combines with hydrogen, reducing its partial pressure to a low value. Thus it is estimated from the data given by Latimer¹⁵ that at 700°K , the partial pressure of hydrogen in equilibrium with barium is $10^{-5.8} \text{ atms}^*$. On the other hand, the overall hydrogen content of the coolant must be kept down so that it does not seriously deplete the Type I reagent in the time period (1 to 2 yrs) over which it must be operative.

* Schump, et al,¹⁶ report dissociation pressures of barium hydride of: < 10 micron ($< 10^{-4.9} \text{ atm}$) and 30 micron ($10^{-4.4} \text{ atm}$) at 623°K and 773°K resp.

References

1. H. Berman, D. Nicoll, H. Poppendiek, C. Rickard, and D. Rose, GAMD-226, (Oct. 1957).
2. P. Fortescue--unpubl. informal meeting on about Feb. 22, 1958.
3. U. Merten, GAMD-230 (Oct. 1957).
4. D. Stull and G. Sinke, Thermodynamic Properties of the Elements, Amer. Chem. Soc. (1956).
5. L. Brewer, L. Bromley, P. Giles and N. Lofgren, Paper 4 in Chemistry and Metallurgy of Miscellaneous Materials, (Ed. L.L. Quill), McGraw-Hill, New York (1950).
6. O. H. Krikorian, High Temperature Studies, II Thermodynamic Properties of the Carbides, UCRL-2888.
7. W. H. Sullivan, Trilinear Chart of Nuclides, ORNL (Jan. 1957). This was taken as most up-to-date compilation of fission product chain yields, but was checked with, and data on independent yields were taken from, the compilation by D. Perkel, L. Leventhal, and L. Zumwalt, Section 8j, Fission-product Chains and Yields, American Inst. of Physics Handbook, McGraw-Hill (1957).
8. L. Brewer, Paper 7 in Chemistry and Metallurgy of Miscellaneous Material: Thermodynamics, (Ed. L. L. Quill), McGraw-Hill, New York (1950).
9. L. Brewer, L. Bromley, P. Giles and N. Lofgren, Paper 6, Chemistry and Metallurgy of Miscellaneous Materials: Thermodynamics (Ed. L. L. Quill), McGraw-Hill, New York (1950).
10. O. Kubaschewski and E. Evans, Metallurgical Thermochemistry, 2nd Ed, Wiley (1956).
11. A. Glassner, ANL-5107 (Aug. 1953).
12. D. Hughes and J. Harvey, BNL-325 (July 1955).
13. A. Helms and W. Klemm, Z.f.anorg. u. allgem. Chemie 242, 201 (1939).
14. L. Brewer, Chem. Rev. 52, 1 (1953).
15. W. Latimer, Oxidations Potentials, 2nd Ed, Prentice-Hall, N.Y. (1952).
16. W. Schumb, E. Sewell, and A. Einstein, JACS 69, 2029 (1947).